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Compressed SPEEDER: Accelerated Magnetic Resonance Imaging Beyond Parallel Imaging

George Matcuck, MD
University of Southern California
Keck School of Medicine

Erin Kelly, Ph.D.
Manager, Medical Affairs
Canon Medical Systems USA, Inc.

Compressed sensing (CS) is a mathematical framework that reconstructs full resolution images from highly undersampled data. Scan times in MRI, with its inherently slow data acquisition process, has historically been a challenge in clinical practice where shorter scan times are typically associated with lower resolution or a lower signal to noise ratio (SNR). To gain acceleration in acquisition time, CS has now been applied to MRI. CS has a natural fit to MRI because the two key requirements for successful implementation of CS are found in MRI data. These are 1) MRI data is naturally *compressible* by sparse coding in an appropriate transform domain (e.g., wavelet transform), and 2) MRI scanners naturally acquire *encoded* samples (spatial-frequency encoding), as opposed to direct pixel samples. This paper will describe how Compressed SPEEDER (CS), Canon's innovative implementation of the compressed sensing framework, supports high acceleration and can be used to avoid artifacts, reduce scan time or increase resolution, and increase SNR. Compressed SPEEDER has great potential to improve clinical productivity.

Towards Rapid Imaging

MR data is acquired by traversing curves in multidimensional k-space. The speed of k-space traversal is limited by physical constraints. For example, gradients are limited by maximum amplitude and maximum slew-rate. Furthermore, physiology provides a strict limit to gradient performance, because high gradient amplitudes and rapid switching can produce peripheral nerve stimulation,[1] which must be avoided. These limitations sparked a fervent scientific search for methods that can reduce the amount of acquired data without degrading image quality. Many of these efforts were inspired by the redundant property in MRI data, redundancy of which is often purposefully designed. For example, using multiple receiver coils[2,3] provides more useful data per MR acquisition, requiring fewer acquisitions per scan. Redundancy can be a known or modeled signal property and importantly, can be extracted from the data itself.[4,5,6]

The Sparsity/Compressibility of MR Images

Digital images can often be compressed with little or no perceptible loss of information.[7] Transform-based compression is a widely used strategy adopted in the JPEG, JPEG-2000, and MPEG standards. This strategy first applies a sparsifying transform, mapping image content into a vector of sparse coefficients, and then encodes the sparse vector by approximating the most significant coefficients and ignoring the smaller ones. The discrete wavelet transform (DWT) is a common sparsifying transform and is central to JPEG-2000.[7] Put simply, wavelets are mathematical functions that separate data into different frequency components, and then evaluate each component with a resolution matched to its scale. Wavelets transforms are advantageous over traditional Fourier methods in analyzing physical situations where the signal contains discontinuities and sharp spikes, such as in CS in which the data is incoherently under-sampled. Many studies have taken place and concluded that a full MR image can be reconstructed from severely undersampled k-space. The realization that MR image compression is possible without resulting in lost information has led to the conclusion that not all of the data is needed in the first place, thus reducing MR scan time without negative side effects.[8]

Fundamentals of Compressed Sensing

The general theory behind CS that a relatively small number of random signals need to be measured—much smaller than the number of signal samples that represent the image. Because the underlying signal is compressible, the nominal number of signal samples is an overestimation of the effective number of "degrees of freedom" of the signal. As a result, the signal can be reconstructed with good accuracy from relatively few measurements by a nonlinear procedure.[9] In MRI, implementation of compressed sensing encompasses acquisition strategy, signal processing, and reconstruction. The key conditions that must be met in order for CS to be successful are as follows:

1. Sparsity: The *data should be sparse* either directly or in an appropriate transform domain (i.e., it must be compressible by transform coding).
2. Incoherent undersampling: The k-space undersampling pattern should cause incoherent (noise-like) artifacts.
3. Iterative reconstruction: The image should be reconstructed by a nonlinear method that enforces both sparsity of the image and consistency of the reconstruction with the acquired samples.

Undersampling in MRI

When MR data is fully sampled, all of the k-space data is available for reconstruction (Figure 1, Full). Sampling only the center of k-space reduces the acquisition time, but results in a blurry image because of the low spatial frequency data (edge information) being eliminated. Parallel imaging techniques, such as SPEEDER, can accelerate data acquisition by *uniformly* undersampling k-space (Figure 1, SPEEDER) resulting in predictable, regular folding artifacts that can only be unfolded using the coil sensitivity maps. Random undersampling (Figure 1, Random) results in artifacts that are incoherent and noise-like, which can be separated from the true signal through an iterative reconstruction process.

Image Sparsity in MRI

The definition of sparsity is thinly scattered or distributed. In an image, sparsity can be visualized by thinking of many black pixels compared to bright ones, such as an angiogram. A typical brain or knee image is not typically considered sparse; but it becomes sparse through its transformation to a different domain—i.e., the wavelet transform (Figure 2). In CS, sparsity is important because the signal can be easily distinguished and separated from the noise. The wavelet domain forces the image to become sparse and makes it easy to identify the amount of pixels that contain relevant information compared to pixels that contain only noise. By setting a threshold above a certain noise level (Figure 3), the incoherent noise will be removed and the output signal mirrors the fully sampled data.

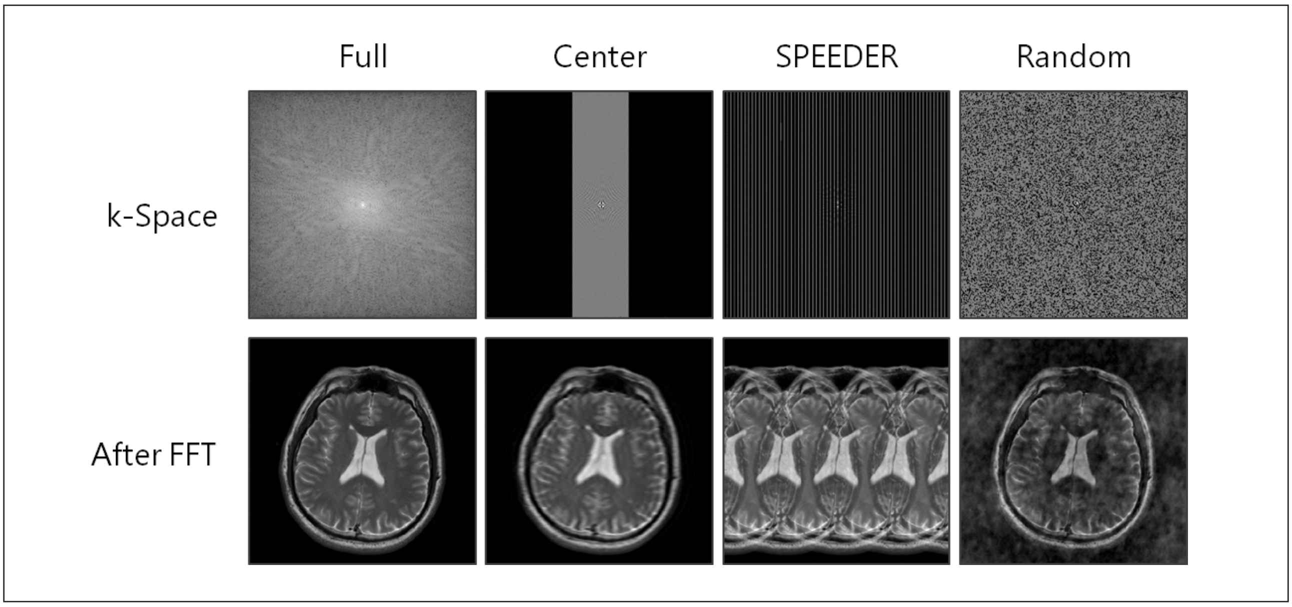

Figure 1. Comparison between full, center only, SPEEDER, and random k-space sampling patterns (top), and their resulting images (bottom).

Multi Element Auto Calibrating Compressed SPEEDER

As mentioned previously, parallel imaging techniques such as SPEEDER, have the ability to accelerate scan times, however, the resulting image quality is dependent on coil sensitivity maps, and high accelerations are limited by coil geometry and anatomy. Due to the reduction of number of acquired samples, SNR is reduced by the square root of the acceleration factor. Furthermore, image reconstruction can contain unfolding artifacts. Combining CS with parallel imaging can be beneficial in that, by including the coil sensitivity maps, the image quality of CS can be improved, provided an alternative sensitivity mapping approach is used. When standard PI is implemented after CS reconstruction, higher acceleration factors can be used, but unfolding errors can degrade image quality. If standard PI were implemented before CS reconstruction, unfolding errors can be eliminated, but image quality with higher acceleration factors suffers. Furthermore, both implementations are limited by the phase encode (PE) direction. CS enables scan time acceleration independent of coil geometry making it possible to use CS even when SPEEDER cannot be used. This approach is called multi sensitivity map for autocalibrating Compressed SPEEDER based on technical improvements combining parallel imaging with autocalibration undersampling algorithms.[10]

k-Space Sampling Strategy

With Compressed SPEEDER, k-space is randomly undersampled to produce the desired incoherent noise pattern. However, suboptimal density distribution can cause blurriness, contain structured noise, and loss of SNR. Compressed SPEEDER utilizes Poisson distribution, a mathematical probability distribution, to optimize k-space and maintain contrast and SNR. The center of k-space is fully sampled and used for the auto-calibration of the

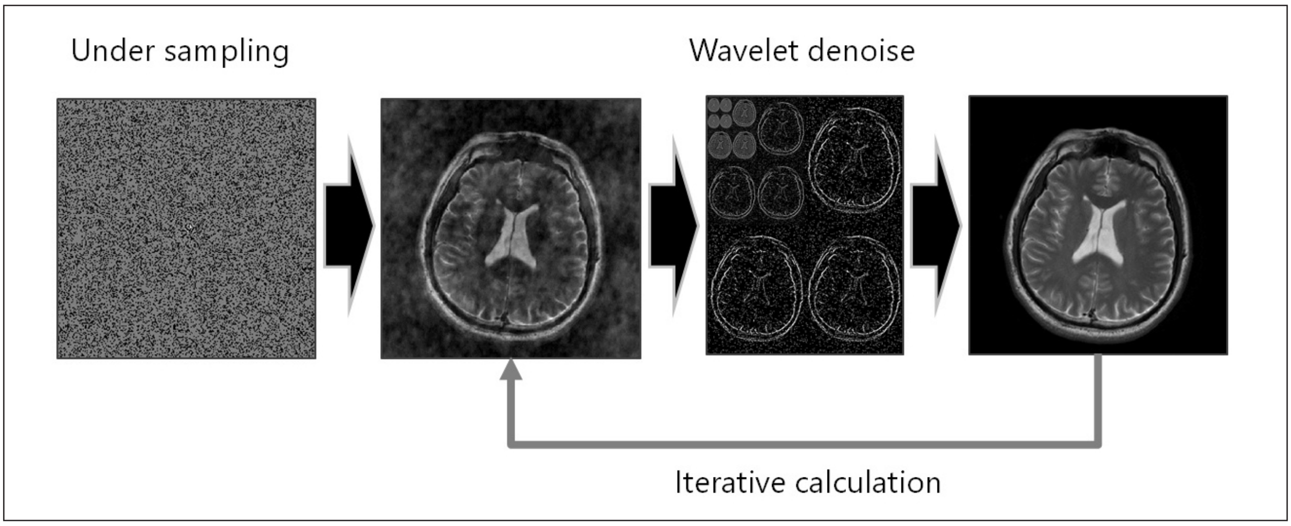

Figure 2. Wavelet transform used for denoising.

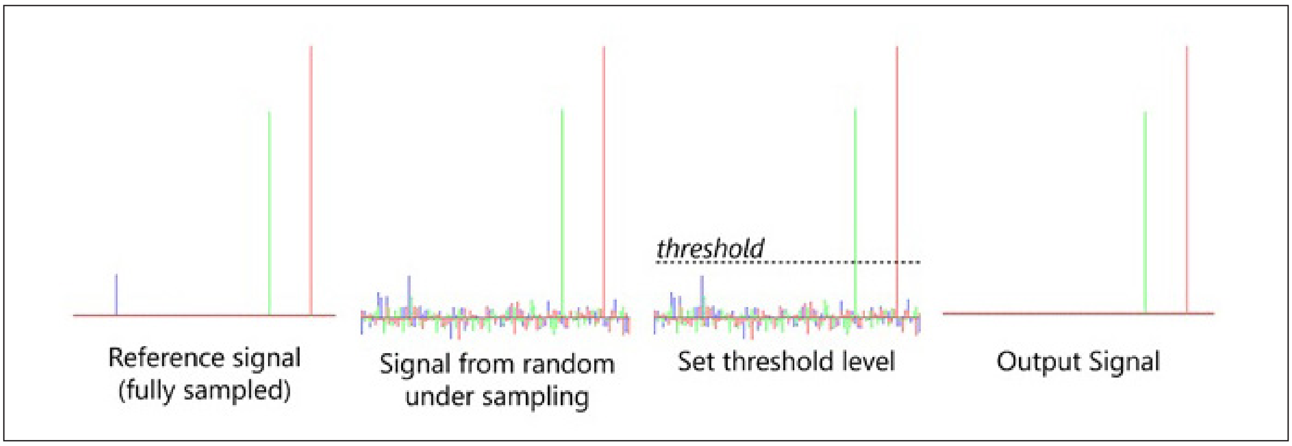

Figure 3. Wavelet thresholding to remove incoherent noise.

sensitivity maps (Figure 4). The entire iterative Compressed SPEEDER process is displayed in Figure 5. To begin, from left to right, a randomly undersampled k-space data pattern with Poisson distribution is employed, multi element sensitivity maps are generated from the fully sampled k-space center. By inverse Fourier Transform, and the sensitivity maps, the initial noisy image is generated. Next, the image undergoes wavelet transformation which separates the image data from the noise in an iterative reconstruction process until the final, fully sampled image is optimally reconstructed.

Compressed SPEEDER in Clinical Practice

Compressed SPEEDER is Canon's implementation of the general high acceleration compressed sensing technique and is easily enabled on the scanner interface (Figure 6). Unlike SPEEDER, CS does not experience edge or unfolding artifacts that can occur with parallel imaging. The incorporation of wavelet denoising inside the iterative CS solution results in a final image with reduced noise. Thus, CS can implement acceleration without the typical corresponding loss in SNR as seen in traditional parallel imaging approaches. CS is currently applicable to FSE2D sequences. To implement CS on the scanner, it is first necessary to turn off SPEEDER and select CS and the chosen acceleration factor (Figure 6, top). The sensitivity maps are auto calibrated with selection of CS. CS acceleration factors correspond directly to the amount of undersampling in k-space. Thus, higher acceleration factors correspond to shorter scan times, and it is important to set the right balance between scan time reduction and image quality. CS can cause blurriness if the CS factor is set too high (less data acquired in the periphery of k-space); this can be counteracted by increasing the matrix size.

The regularization factor (λ) is the second parameter that can be set for CS acquisition (Figure 6, bottom). Effectively, λ is used in the iterative reconstruction of the CS image and to set the balance between image noise and image blurring.

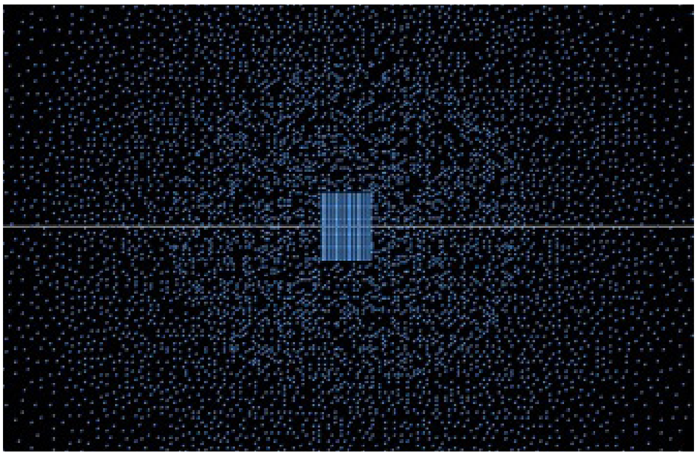

Figure 4. Compressed SPEEDER k-space distribution displaying a fully sampled k-space center and optimized undersampling in the periphery.

Figure 6. User interface for Compressed SPEEDER

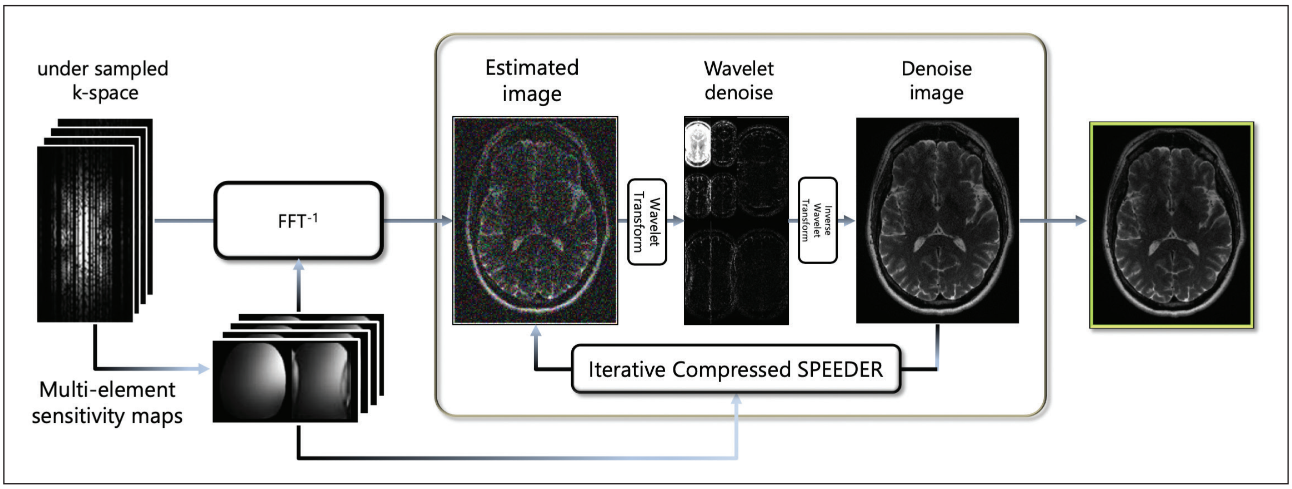

Figure 5. Compressed SPEEDER Flowchart

Setting a high regularization factor significantly reduces noise but results in image blurriness. Likewise, too low of a regularization factor reduces blurriness, but increases noise.

Clinical Evaluation

FSE2D CS has been clinically evaluated at the University of Southern California Keck School of Medicine. In this systematic study conducted under IRB approval, patients agreed to undergo their knee exam with multiple acceleration factors of three sequences in addition to the standard routine exam. These images were then anonymized and randomized before review by two experienced radiologists and given a score of 1-4, where a score of 1 represents an image with poor quality and an image with a score of 4 is considered very good. The results were presented at the 2018 Radiological Society of North America's scientific conference.[11-13] The clinical protocol (Table 1) was repeated with four additional CS sequences as shown in Table 2 with corresponding reduced scan times. A regularization factor of 1.6 was used for all CS scans.

The results of the inter reader image quality study are shown in Figure 7. Compressed SPEEDER performed comparably to the routine exam in all factors measured, according to the radiologists' review. All images were considered diagnostic.

With an ever growing need for access to MRI scans, speed is an important factor. Considering these results, significant

	Axial PD FS	Coronal T1	Sagittal T2 FS
Echo train length (ETL)	7	2	9
Echo time (TE)	44 ms	11 ms	55 ms
Repetition Time (TR)	3108 ms	525 ms	3516 ms
Flip Angle	90	90	90
Number of excitations	2	1	1
Matrix size	224 x 384	192 x 448	384 x 192
Field of view (FOV)	16 x 17.4 cm	16 x 17.4 cm	16 x 17.4 cm
Slice thickness	3 mm	3 mm	3 mm
Interslice gap	1 mm	1 mm	1 mm
Number of slices	30	24	24

Table 1. Clinical knee protocol used at USC Keck School of Medicine.

	Axial PD FS	Coronal T1	Sagittal T2 FS
Standard FSE	04:52	04:30	02:52
CS 2.0	02:48	02:16	02:16
CS 2.4	02:20	01:56	01:52

Table 2. Sequences repeated with CS and corresponding scan time.

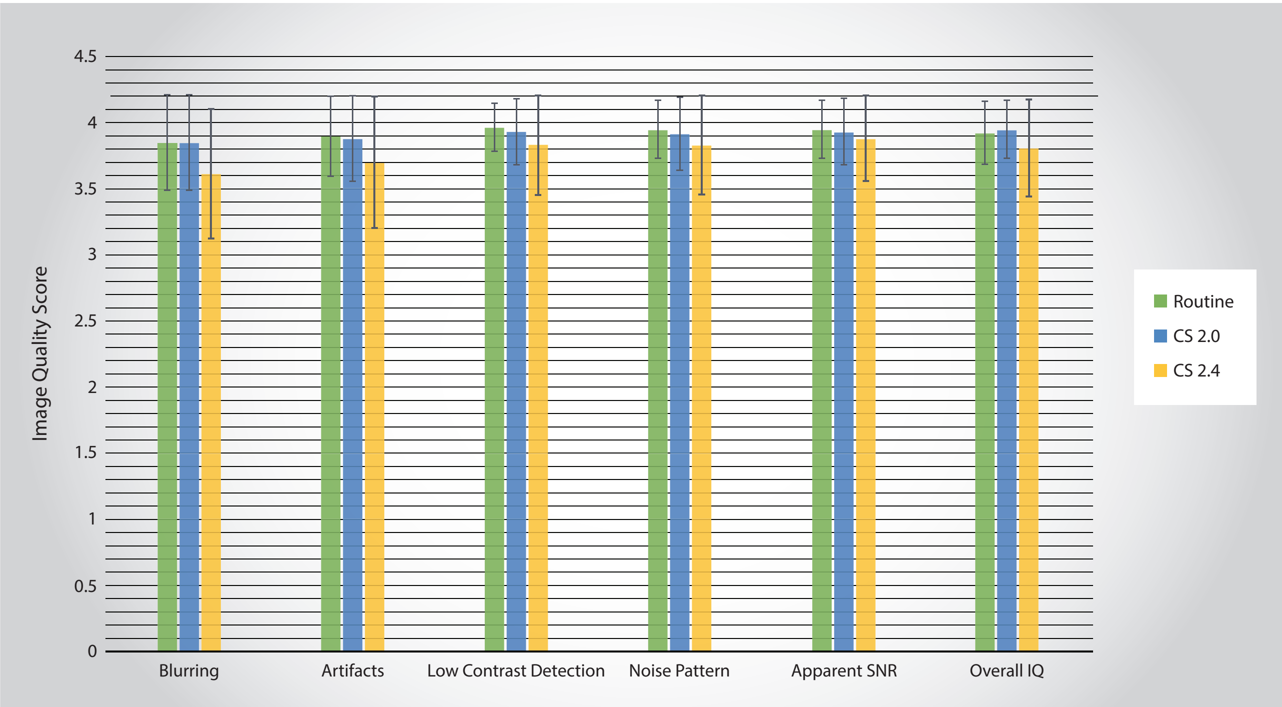

Figure 7. Results of Image Quality Study. A score of 1 represents an image with poor quality and an image with a score of 4 is considered very good.

time savings is an immediate payoff from implementing CS without loss of diagnostic information. Replacing just three routine FSE2D sequences would result in significant time savings without losing diagnostic information.

Example comparison images between routine Axial Proton Density Fat Sat, Coronal T1, and Sagittal T2 Fat Sat and the same sequences repeated with CS2 and CS2.4 are shown in Figures 8, 9, and 10, respectively. In all cases, diagnostic image quality was supported and significant scan time reductions were achieved (see Table 3).

Compressed SPEEDER in the Clinical Setting

Compressed SPEEDER can be applied to FSE2D sequences and has many benefits. An obvious and practical application is reduced scan time. For sick and/or elderly patients, in cases of claustrophobia, pediatrics, shorter scan times are essential. Other potential uses of shorter scan times include increased throughput, or obtain higher resolution. It is also possible to use CS

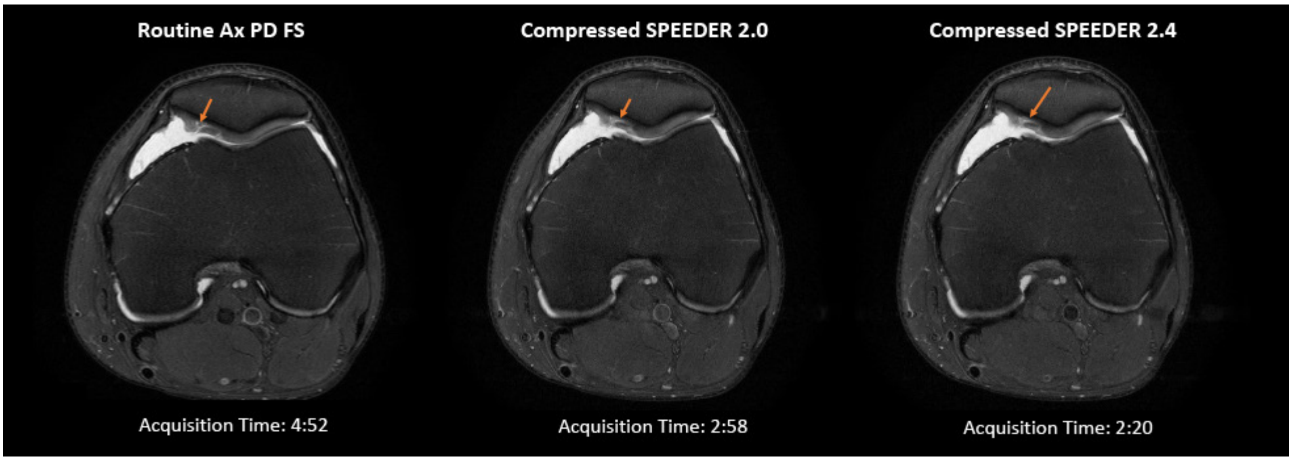

Figure 8. A 42-year-old man presented with chondromalacia patellae. Grade 3 chondral fissuring and delamination of the medial patellar facet is clearly demarcated with similar quality with acquisition time savings of up to 52% with CS rate 2.4.

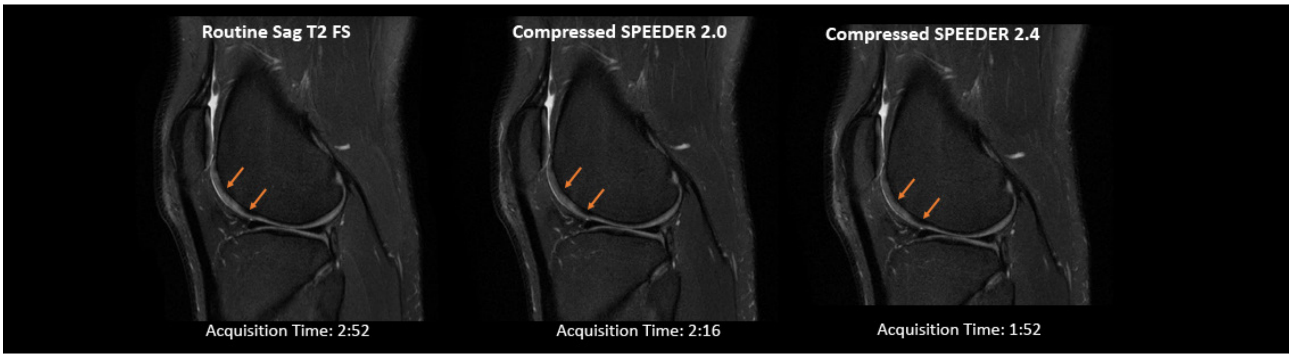

Figure 9. A 22-year-old man presented with lateral trochlear chondrosis. Signal alteration (low grade chondrosis) of the lateral trochlear cartilage is defined on each image.

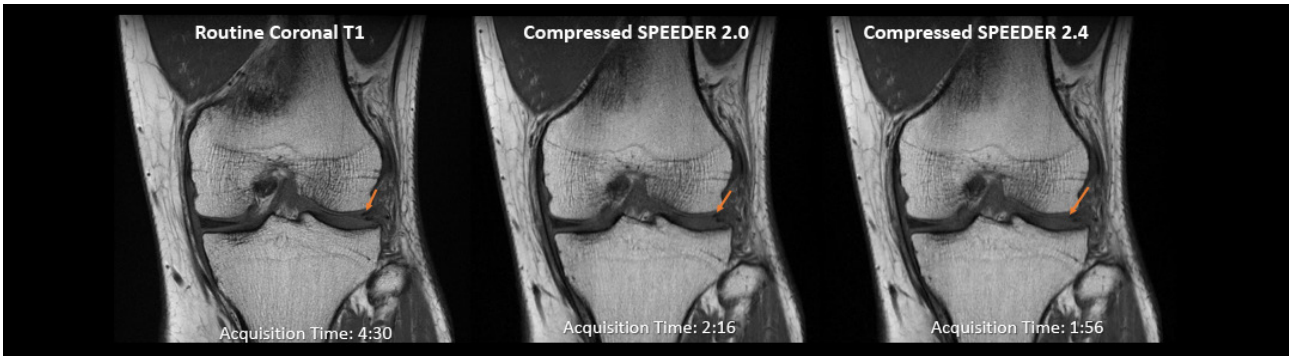

Figure 10. A 37-year-old man presented with a lateral meniscal tear. Compressed SPEEDER reduced the standard acquisition time by 50%-60%.

where standard parallel imaging cannot be used, or add additional sequences. An additional benefit is the counter intuitive relationship between CS acceleration and SNR due to the built-in wavelet denoising; SNR can increase with acceleration under certain conditions. In addition, because CS is less sensitive to coil geometry, problematic parallel imaging artifacts can be avoided.

As with all advancements, it is important to keep in mind their limitations. An excepted scan time reduction of 40-50% is reasonable and can be attained without compromising image quality. CS acceleration with factors between 2-2.5 will provide a reasonable amount of time savings while supporting diagnostic image quality. A montage of various applications of Compressed SPEEDER using FSE is shown in Figure 11.

Summary

With optimized k-space undersampling, while maintaining the fully sampled center of k-space, Compressed SPEEDER supports accelerated acquisitions without dependence on PE direction, and eliminates unfolding artifacts. Further research and development may bring Compressed SPEEDER into additional clinical applications.

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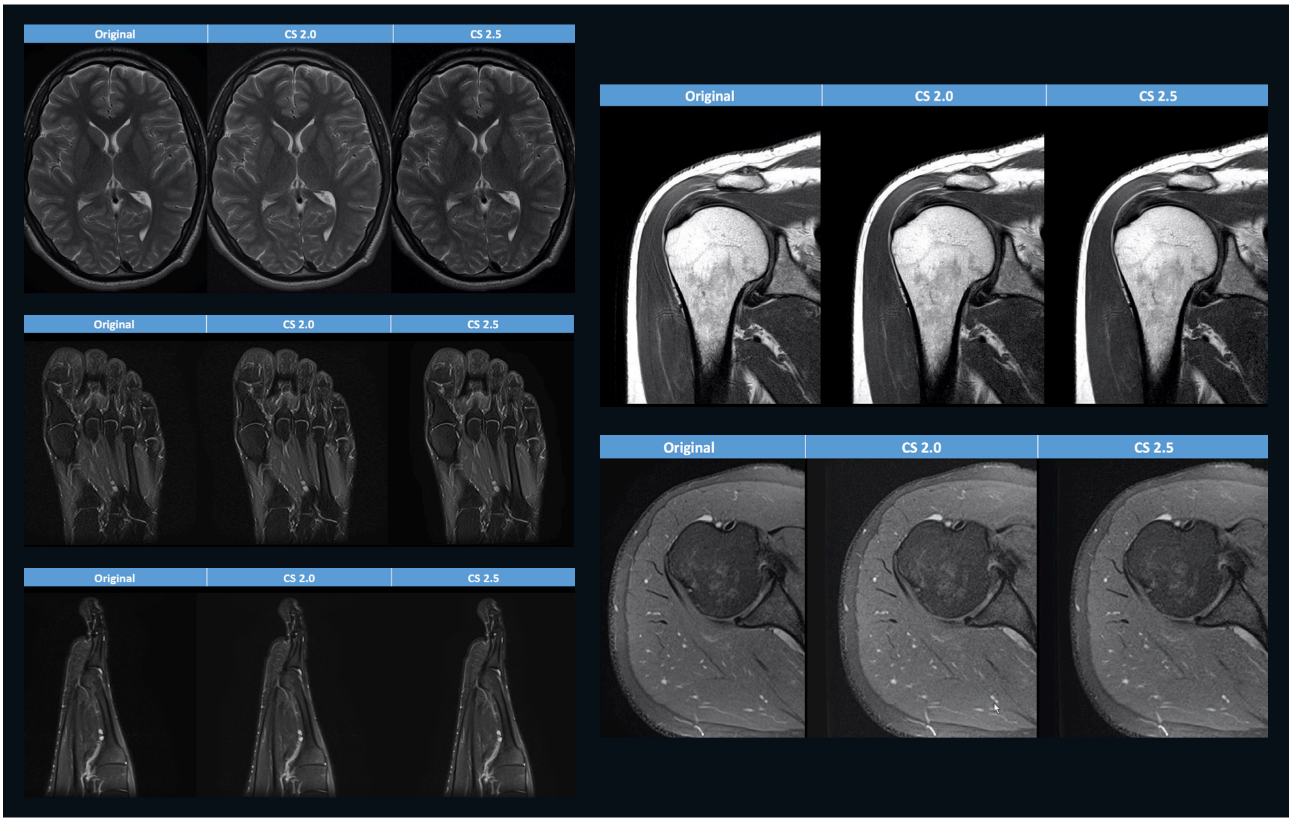

Figure 11. Montage of images acquired with no acceleration, Compressed Speeder 2 and Compressed SPEEDER 2.5.

Anatomy	Sequence	Matrix	Scan Time (No Acceleration)	Scan Time (Compressed SPEEDER 2)	Scan Time (Compressed SPEEDER 2.5)	% Time Savings
Brain	FLAIR	256 x 256	5:04	2:56	2:24	**52.6**
Shoulder	Cor PD	352 x 352	6:12	3:07	2:30	**59.7**
Shoulder	Ax PD FS	256 x 256	7:03	3:33	2:52	**59.3**
Toes	PD FS	256 x 256	5:32	2:52	2:20	**57.8**
Toes	Sag STIR	256 x 256	6:30	4:06	3:19	**49.0**

Table 3. Parameters and acquisition times are shown.

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The clinical results, performance and views described in this white paper are the experience of the author. Results may vary due to clinical setting, patient presentation and other factors. Many factors could cause the actual results and performance of Canon’s product to be materially different from any of the aforementioned.

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